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Report No. 170

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WET - COLD I

EFFECT OF MOISTURE ON TRANSFER OF HEAT THROUGH INSULATING MATERIALS

Quartermaster Climatic Research Laboratory

Research and Development E
Military Planning Division
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Military Planning Division

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Report No. 170

WET - COLD I

EFFECT OF MOISTURE ON TRANSFER OF HEAT THROUGH INSULATING MATERIALS

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Lawrence, Massachusetts

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RESUME

EFFECT OF MOISTURE ON TRANSFER OF HEAT THROUGH INSULATING MATERIALS

Requirements

a. To develop a theory accounting for the increased heat loss through wetted insulating materials.

b. To observe effects of wetting on heat loss through selected textile materials and relate findings to the theory that has been developed.

c. To consider principles which may be utilized to minimize heat loss through clothing which is worn under conditions where wetting may be expected.

Method

Using the basic principles of moisture diffusion and heat transfer, relations between rate of drying, rate of heat transfer, drying time and location of moisture have been derived. Representative computations have been made for completely wicking and completely non-wicking insulating materials. Textile materials with widely different wicking properties were then selected for study. These included Harris tweed suiting, OD serge, and cotton flannel. The time course of heat transfer through each of these fabrics after wetting was then determined using a flat plate heated to 92°F. in a constant temperature room at 30°F. and a relative humidity of 75 per cent ±5 per cent.

Results

a. For perfectly wicking materials the theory predicts that the rate of heat loss is constant during the drying period, then drops suddenly to the normal value for dry insulation when all moisture is evaporated. For such materials, the theory also predicts that the additional heat required during the drying period is considerably in excess of the latent heat of the water evaporated.

b. For perfectly non-wicking materials, the theory predicts that the rate of heat loss decreases steadily during the drying period due to redistribution of moisture through the insulation. Because of this redistribution, the additional heat required during the drying period is much less than the latent heat of the water evaporated. The theory assumes the rate of moisture loss is proportional to the rate of heat loss and since the rate of heat loss decreases with time, the drying takes longer to complete than with a wicking material.

c. The experimental results agreed in principle with the theory. Discrepancies between theoretical predictions and experimental results could be traced to variations in initial moisture distribution in the test fabrics.

d. Experiments with cotton flannel with good wicking qualities indicated a constant heat loss (to within 10 per cent) while the material contained moisture. On completion of drying, the rate of heat loss dropped suddenly by 48 per cent to the value for dry insulation. An additional heat of 633 calories per gram was lost while the moisture was evaporating, which is greater than the latent heat of water.

e. Similar experiments with OD serge and Harris tweed, with fair and poor wicking characteristics, respectively, indicated a continual decrease in rate of heat loss as drying proceeded. The rate with OD serge decreased gradually for the first half of the drying period, then fell off more rapidly and approached the value for dry insulation. With Harris tweed the initial rate of heat loss was less than with cotton or OD serge and decreased steadily through a relatively long drying period. The average additional heat required for drying Harris tweed was 278 calories per gram.

f. Experiments with two layers of cotton flannel in contact indicate, that, although wicking within layers took place there was little water transfer between layers when undisturbed. With both layers initially wet, the changes in temperature at the interface as drying proceeded agreed qualitatively with theoretical predictions.

Applications

a. It would appear from the point of view of body heat conservation that clothing which is worn under conditions where wetting is a possibility should be composed of materials which wick a minimum of moisture. Such wetting may be the result of immersion in water, heavy rain, and to a lesser degree, drizzle of rain and fog.

b. In wet-cold areas, clothing consisting of fabrics with poor wicking characteristics would appear to offer an advantage. In a light drizzle or fog, such clothing will be wetted only on the outermost layers and the heat loss due to evaporation will be small. Wicking fabrics, on the other hand, would transfer moisture to the inner layers resulting in a much larger heat expenditure.

c. A new interpretation of Brynje, or net, underwear is suggested by the theory. Such underwear in effect maintains a fixed air space next to the skin in which water cannot accumulate. When the clothing begins to dry following wetting by sweat or rain, the heat loss is much less than if the layer next to the skin were wet.

d. Computations based on the theory have been made for only one set of conditions, namely, 0°C. and 100 per cent relative humidity at the cold boundary, 30°C. at the hot boundary, and the insulation uniformly wetted. It might be of interest to extend the theory to the case of an initially dry fabric to which moisture is added at the hot boundary, i.e., a sweating man; and to extend the computations to different temperatures and humidities at the cold boundary, i.e., different environmental conditions. Such computations may give a clearer insight of the role of humidity under wet-cold conditions.

Project Reference

This investigation was performed as proposed Work Phase entitled "Heat Transfer Through Wet Fabrics" under Project No. 7-64-06-001, "Principles of Protection Against Cold".

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EFFECT OF MOISTURE ON TRANSFER OF HEAT THROUGH INSULATING MATERIALS

1. Introduction

a. Contained moisture has long been known to increase the heat transfer through insulating materials. This has been considered an important problem in such fields as refrigeration engineering, building construction and clothing design. Investigations have mainly centered on vapor transmission with the objective of preventing condensation or predicting when and where it will occur rather than on the mechanisms by which moisture augments heat flow.[5,6,11,12]

b. Nevertheless, some work has been done on the measurement of reduction of insulation caused by the presence of moisture.[8,1] The work of Hock, Sookne and Harris[9] has shown that the nature and construction of the materials are important factors in the initial stages of heat loss in moist textiles. Related, in that they indicate special processes by which moisture may be transferred, are the results of Robinson,[10] who has indicated that in wet fibrous insulation some movement of liquid water may take place. Also, Baxter and Cassie[2] have worked out a very comprehensive theory of wetting and the capillary effects in fibrous insulation.

c. This paper is intended to present a preliminary analysis of heat transfer by evaporation and by migration of the free moisture within insulation. The first part of the paper discusses some of the theoretical aspects of heat transfer through moist insulation while the second part describes actual heat losses through several types of materials during drying and interprets the results in terms of the theory. While the moisture absorbed by the fibers themselves is doubtless of importance[4] when considering materials of relatively low total moisture contents, its effect may be of less relative importance when the moisture content of the insulation is high.

2. Theory

a. General

(1) In treating this problem theoretically an idealized situation will be considered. It will be assumed that an homogeneous uniform of initially uniformly wetted material is bounded on one side by a hot, moisture-impermeable surface of constant temperature and on the other by a constant temperature cold surface from which moisture can escape. This situation is applicable to a layer of wet clothing worn over a relatively warm skin in cold weather. Moreover, it is assumed that all moisture escapes from the cold boundary in the vapor state and at this boundary the atmosphere is saturated with water vapor.

(2) In dealing with dry insulation in which the heat transfer is as sensible heat (i.e., heat which raises the temperature), its

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transfer is generally given by the equation of conductive heat transfer, namely:

$$H_s = -k \frac{dt}{dx} \qquad \text{Equation 1}$$

where H_s is the rate of sensible heat flow per unit area,

k is the thermal conductivity and

$\frac{dt}{dx}$ is the temperature gradient at any point x in the insulation.

For uniform flat insulation in temperature equilibrium, this equation becomes:

$$H_s = -k \frac{(t_2 - t_1)}{x} \qquad \text{Equation 2}$$

where t_1 and t_2 are the temperatures of the cold and hot sides, respectively, and x is the total thickness of insulation. If, however, the insulation is not uniform, then we must revert to the differential form of Equation 1. If there is no change in temperature with time, the heat flowing past two points is constant and it follows that, for a unit area, $H_s = -k \frac{dt}{dx}$ at all points throughout the insulation. The differential form of this equation is

$$H_s \, dx = -k \, dt$$

Integrating with x and the outer surfaces of the insulation as limits

$$H_s \int_{x=0}^{x=x} dx = -\int_{t_1}^{t_2} k \, dt$$

we get the expression for sensible heat flow through non-uniform insulation

$$H_s \, x = -\int_{t_1}^{t_2} k \, dt$$

Dividing through by x

$$H_s = -\frac{\int_{t_1}^{t_2} k \, dt}{x} \qquad \text{Equation 3}$$

This equation will be compared with one derived later.

(3) In wet insulation, heat may be transferred by both thermal conduction (sensible heat) and by evaporation (latent heat). If "m" units of moisture of latent heat "L" are evaporated at point A and flow to point B where condensation occurs, then not only will "m" units of moisture be transferred from A to B, but also "mL" units of heat. In general, we may say that when "m" units of moisture pass any point "x" in vapor form "mL" units of latent heat also pass. Specific heats of both water and insulation are not considered in this theoretical treatment since they are regarded as negligible in comparison with the latent heat of evaporation. To illustrate this, consider an insulating material whose boundaries are at 0° and 30°C. One would expect the average temperature of water distributed uniformly through it to be at about 15°C. Thus, a gram of water in the insulation would require 15 calories to heat it from 0°C. to its average temperature. The latent heat of evaporation of water is 595 cal. per gm. or about 40 times as great. Hence, the error in neglecting the specific heat of the water in this insulation is about 2-1/2 per cent. The error in neglecting the specific heat of the insulation can similarly be shown small in comparison to the latent heat of water unless the moisture content of the insulation is very low.

(4) The rate of moisture vapor passing any point x in a porous or fibrous insulation is dependent on the characteristic resistance of the insulation to diffusion.[7] In this treatment this will be considered as constant (i.e., it does not vary with temperature or from point to point through the insulation). In addition, the diffusion rate is proportional to the concentration gradient of water vapor. However, since the concentration is very closely proportional to the vapor pressure, we may conclude that the diffusion of water vapor through insulation is proportional to the vapor pressure gradient. Furthermore, since the insulation is wet, we may assume the vapor pressure of water is the saturated vapor pressure. It will be shown later that at all points throughout the wet insulation, the condensation rate is greater than the evaporation rate so that saturation occurs at all points provided the wet insulation is saturated at the hottest part. This result can then be written:

$$H_L = -b \frac{dp}{dx} \qquad \text{Equation 4}$$

where H_L is the latent heat transfer past the point x

b is a constant

$\frac{dp}{dx}$ is the gradient of saturated vapor pressure at any point x in the insulation.

(5) Since the total heat, H_W, flowing through the insulation is the sum of H_S and H_L, and since the total heat flow is constant throughout the insulation, we may write:

$$H_W = H_S + H_L = -k\frac{dt}{dx} - b\frac{dp}{dx}$$

$$= -k\frac{dt}{dx} - b\frac{dp}{dt} \cdot \frac{dt}{dx}$$

or

$$H_W = -\frac{dt}{dx}\left(k + b\frac{dp}{dt}\right) \qquad \text{Equation 5}$$

Equation 5 is the fundamental equation for heat transfer through wet insulation. Comparing it with Equation 1 we will see that for k we must substitute $\left(k + b\frac{dp}{dt}\right)$ which is now no longer a constant but varies with t. It is, therefore, comparable to an insulation with variable thermal conductivity and we may say that:

$$\int_{t=t_1}^{t=t_2}\left(\frac{k}{b} + \frac{dp}{dt}\right)dt$$

will be proportional to the heat flow through the insulation.

(6) Since $\frac{dp}{dt}$ is not a simple algebraic function, it is not possible to simplify Equation 5 further, and numerical approximations must be made. Let us, then, turn to a typical application to clothing and assume a hot boundary temperature of 30°C. (86°F.), or approximately skin temperature, and a cold boundary temperature of 0°C. (32°F.), or freezing. Total thickness of the insulation will be taken as unity and any point within it is specified by "x", the distance from the cold boundary. Thus x = 0 represents the cold boundary and x = 1 represents the hot boundary while x = .25 represents a point one-quarter of the total linear thickness of the insulation from the cold boundary. On the basis of experimental results, the ratio $\frac{k}{b}$ may be considered to be about 0.6, when $\frac{dp}{dt}$ is expressed in mm. of mercury per centigrade degree. In the expression $\left(\frac{k}{b} + \frac{dp}{dt}\right)$, $\frac{dp}{dt}$ is zero when the insulation is dry. That is, $\frac{k}{b}$ represents the sensible heat transfer past a point x and $\frac{dp}{dt}$ represents the latent heat transfer. At 0°C., $\frac{dp}{dt}$ is 0.334. This means that for every 0.6 units of sensible heat appearing at the cold boundary, 0.334

units of latent heat appear giving a total of 0.934 units. This is determined experimentally by observing the moisture and total heat loss from a piece of wet insulation on a heated plate. The moisture loss in grams times the latent heat represents the latent heat loss which was found to be proportional to 0.334 while the total heat loss was proportional to 0.934.

b. Bibulous Insulation

(1) The first example is based on an idealized piece of insulation which is wet and which is considered perfectly bibulous or perfectly wicking. Since the vapor pressure is highest where the temperature is highest, evaporation takes place at the hot boundary. Moreover, this moisture, because of its higher vapor pressure, diffuses toward the cold boundary. The factor $\frac{dp}{dx}$ which governs its diffusion rate is highest at the hot boundary and decreases as the cold boundary is approached. Therefore, provided there is saturation at the hot boundary, as we assume, there is some condensation throughout the insulation as well as some escape of vapor at the cold boundary. With bibulous insulation, that moisture which condenses wicks back to the warm boundary and re-evaporates. Thus, the insulation is assumed wet throughout until all the moisture is evaporated when it suddenly becomes dry.

(2) From Equation 5 we may calculate the relative increase in heat loss due to wetting and the temperature distribution within the insulation. The heat loss when the insulation is wet will be expressed in terms of the heat loss when dry. The ratio of these two heat losses will be called the power ratio. Equation 5 can be expressed as:

$$\frac{H_w}{b} = -\frac{k}{b}\frac{dt}{dx} - \frac{dp}{dt}\frac{dt}{dx}$$

or

$$\frac{H_w}{b}\,dx = -\frac{k}{b}\,dt - \frac{dp}{dt}\,dt$$

and integrating between x and the cold boundary as limits

$$\frac{H_w}{b}\int_0^x dx = -\frac{k}{b}\int_0^t dt - \int_{p_0}^{p_t} dp$$

where p_0 is the vapor pressure at 0°C., and p_t is the vapor pressure at t°C., this equation becomes:

$$\frac{H_w\,x}{b} = -\frac{k}{b}\,(t - 0) - (p_t - p_0) \qquad \text{Equation 6}$$

Similarly, the heat loss through dry insulation is given by

$$\frac{H_d\ x}{b} = -\frac{k}{b}\,(t - 0) \qquad \text{Equation 7}$$

where H_d is the heat loss through dry insulation. Using t as the temperature of the hot boundary, i.e., 30°C., and dividing Equation 6 by Equation 7, we get the power ratio (pr).

$$pr = \frac{H_w}{H_d} = \frac{-\frac{k\ (30 - 0)}{b} - (p_{30} - p_0)}{-\frac{k\ (30 - 0)}{b}}$$

$$pr = \frac{0.6\ (30 - 0) + (31.824 - 4.579)}{0.6\ (30 - 0)}$$

$$= \frac{18 + 27.245}{18} = 2.52$$

Thus, the rate of heat loss during drying will average 2.52 times that when the material is dry.

The temperature distribution across the insulation may be determined as follows:

x at temperature t is given by Equation 6:

$$\frac{H_w\ x}{b} = -\frac{k}{b}\,(t - 0) - (p_t - p_0)$$

If x = 1 at the hot boundary (i.e., we consider our insulation one unit thick) and x = x at any intermediate point, then

$$\frac{\frac{H_w\ x}{b}}{\frac{H_w\ 1}{b}} = \frac{\frac{k\ (t - 0)}{b} + (p_t - p_0)}{\frac{k\ (30 - 0)}{b} + (p_{30} - p_0)}$$

$$x = \frac{\frac{k\ (t - 0)}{b} + (p_t - p_0)}{\frac{k\ (30 - 0)}{b} + (p_{30} - p_0)} \qquad \text{Equation 8}$$

From Equation 8 we may compute the value of x for various values of t.

Figure 1 shows the temperature distribution for such bibulous insulation. Figure 4 shows the moisture content and power ratio as functions of the time of drying.

It has been shown above that the power ratio is 2.52. Therefore, the presence of moisture increases the heat loss by 1.52 or causes $\frac{1.52}{2.52}$ of the total heat loss. The amount of heat leaving the cold boundary is in the ratio of 0.334 units of latent heat to 0.934 units of total heat. Thus, an excess of $\frac{1.52}{2.52}$ or 60.4 per cent of the total heat loss results in only $\frac{0.334}{0.934}$ or 35.7 per cent actually leaving the surface as latent heat. Thus, the apparent latent heat is $\frac{60.4}{35.7}$ or 1.687 times the true latent heat.

or

$$\frac{\text{apparent latent heat}}{\text{true latent heat}} = \frac{1 - \text{power ratio}}{\text{power ratio}} \times \frac{0.934}{0.334}$$

The apparent latent heat is greater than the true latent heat because some of the evaporated moisture is condensed in the insulation, wicked back to the hot boundary, and re-evaporated.

c. Non-bibulous Insulation

(1) Now let us turn to the case of completely non-bibulous insulation, where moisture is moved as a vapor only. In this case the hotter layers of insulation transfer moisture in the vapor phase to the cooler layers. Thus, the warmer layers become dry. When this occurs, then only sensible heat is transferred in the dry portion.

If y is the position of the wet-dry boundary whose temperature is t_y, then from 0 to y Equation 5 becomes:

$$\frac{H_W}{b}\int_0^y dx = -\frac{k}{b}\int_0^{t_y} dt - \int_{p_0}^{p_{t_y}} dp$$

and from y to 1, it becomes:

$$\frac{H_W}{b}\int_y^1 dx = -\frac{k}{b}\int_{t_y}^{30} dt$$

Adding these two equations:

$$\frac{H_W}{b}\left[\int_0^y dx + \int_y^1 dx\right] = -\frac{k}{b}\left[\int_0^{t_y} dt + \int_{t_y}^{30} dt\right] - \int_{p_0}^{p_{t_y}} dp$$

or

$$\frac{H_w}{b}\int_0^1 dx = -\frac{k}{b}\int_0^{30} dt - \int_{p_0}^{p_{t_y}} dp$$

The power ratio then becomes:

$$pr = \frac{H_w}{H_d} = \frac{\frac{k\,(30 - 0)}{b} + (p_{t_y} - p_0)}{\frac{k\,(30 - 0)}{b}} \qquad \text{Equation 9}$$

The temperature distribution across the insulation is found in a similar manner to that used for bibulous insulation.

Here Equation 8 becomes:

$$x = \frac{\frac{k\,(t - 0)}{b} + (p_t - p_0)}{\frac{k\,(30 - 0)}{b} + (p_{t_y} - p_0)} \qquad \text{Equation 10}$$

If, however, $x > y$, p_t must be given the value p_{t_y}. This is because in the section of the insulation which is dry (i.e., $x > y$) p_t must equal p_{t_y}. If in the section $x > y$, p_t were not equal to p_{t_y} then diffusion would occur until it was.

It will be observed in all these computations a value of t was selected and the value of x computed. Thus, t is the independent variable and x the dependent variable.

(2) To obtain the graph of rate of drying, it was necessary to replot these curves with x as the independent variable. The rate of heat loss, redistribution of moisture and time of drying was then calculated in twenty successive steps. The moisture content and power ratio are plotted against time in Figure 4.

(3) It will be noticed in Figure 2 that the temperature of the midpoint of the insulation is initially higher than the mean temperature of the hot and cold boundaries; in these calculations it is 18.6°C. As drying progresses it drops to 10.7°C. when half the insulation is dry. As the drying is completed, the temperature of the midpoint rises to the mean of 15°C.

(4) The moisture distribution in the insulation can also be followed (Figure 5). Since, in the wet section of the insulation the temperature curve is convex upwards, it follows that there is greater latent heat and moisture transfer at the warm side. Thus, any point in the wet portion receives more latent heat and moisture than it gives off (see 2 b (1), above). The result is that the moisture content per unit volume of the wet portion increases with time. It will be seen that the moisture content near the cold boundary rises to nearly double the original value. If the insulation is initially saturated, then it may become oversaturated during drying, and, if vertical, some moisture may drain off.

(5) The apparent latent heat ratio for non-bibulous insulation is calculated in the same manner as for bibulous insulation. It is given by

$$\frac{1 - \text{power ratio}}{\text{power ratio}} \times \frac{0.934}{0.334}$$

For non-bibulous insulation the apparent latent heat ratio varies with y, the distance of the wet-dry boundary from the cold boundary. When y = 1 the apparent latent heat ratio is the same as for the bibulous insulation but it decreases as y decreases (Figure 3). As y approaches zero, this ratio also approaches zero. This means that when moisture is present only on the cold surface of insulation, it can evaporate without additional heat transfer. Examples of this might be considered as rain falling on the outside of a raincoat or snow on the outer surface of clothing. The apparent latent heat ratio integrated from y = 1 to y = 0 or during total drying time is calculated to be 0.456.

At first inspection, it might be considered that it should be 0.5 because the moisture initially being uniformly distributed throughout the insulation could be considered as concentrated at the center point, in which case the effect of heat absorbed as latent heat could be calculated by Burton's formula[3] which was derived for the efficiency of electrically heated clothing. This formula states that the fraction of the heat which affects the hot boundary is given by $\frac{I_{xo}}{I_{xo} + I_{xi}}$, where I_{xo} is the insulation between the cold boundary and the point x within the insulation where the heat is applied and I_{xi} is the insulation between the hot boundary and the point x. $I_{xo} + I_{xi}$, therefore, equals the total insulation. However, Burton's formula is based on resistance to heat transfer on either side of x. In this problem, the resistance to heat transfer of the insulation varies with time. For example, the section of the insulation between x = 0 and x = 0.5 represents (Figure 2) $\frac{18.6}{30}$ or 62 per cent of the total heat resistance in the initial phase of drying

when all the insulation is wet. In other words, the temperature drop through the colder half of the insulation is 18.6 C° which is $\frac{18.6}{30}$ of the total temperature drop. Therefore, a unit of moisture evaporated at $x = 0.5$ will have an apparent latent heat ratio of 0.62. When only the cooler half is wet, the heat resistance from $x = 0$ to $x = 0.5$ is only $\frac{10.7}{30}$ or 35.7 per cent of the total. Hence, the apparent latent heat ratio has decreased to 0.357. Burton's formula would be applicable to this problem only if account were taken of relative change with time in heat resistance of each portion of the insulation.

(6) It should be realized that the theory presented above deals only with insulation which is heated on the face opposite to that from which evaporation occurs. It is, therefore, inapplicable to air drying problems without an internal heat source or to drying by radiant or high frequency electrical heating. Moreover, it considers only heat transfer by conduction and evaporation neglecting the effect of convection and radiation. The calculations based on the theory contained many simplifying assumptions; e.g., constant values for k and b, but most of these are valid for approximate work. In consequence, calculations should not be made using the theory to give exact quantitative predictions of any particular drying process. However, the shapes of the drying curves and values of apparent latent heats for wicking and non-wicking materials differ so greatly that it is considered the theory might be of use for qualitative assessment and interpretation of some of the observed phenomena in drying processes of this type.

(7) To examine the applicability of the theory, typical pieces of cloth were selected, wetted, and dried on a heated plate. In testing in this manner, it was realized that there was an insulating layer of relatively still air over the cloth. Furthermore, the nap and body of the cloth probably vary in moisture retaining qualities, wicking action, thermal conductivity, and resistance to diffusion of water. However, the practical use of the theory could only be proved by whether it could interpret experimental results or whether other factors would mask the theoretical predictions.

3. Materials and Methods

a. The experimental tests consisted of wetting samples of cloth, placing them on a Guard Ring Flat Plate and following the power requirements and moisture loss as they dried out. The Flat Plate, maintained at 92°F., was mounted on a scale capable of being read to within one gram and placed in a constant temperature room maintained at 30°F. Automatic humidity control was not available. However, by the use of wet sheets hung in the room, humidity was maintained at 75 per cent ±5 per cent.

The wetted cloth was placed directly on the Flat Plate and readings of the power required in the test section and the weight of cloth were recorded at regular intervals until the cloth was dry. Temperatures were recorded by thermocouples lying between the cloth and plate, on top of the cloth and, when two layers of cloth were used, between the layers.

b. To obtain a qualitative check on the wicking action of the materials tested, a simple wicking test was set up. The ends of one-inch strips of cloth were dipped in an elevated evaporating dish full of water. The other end hung down from the edge of the dish and a 100 ml. beaker was placed below it. Water from the evaporating dish wicked up the strips to the edge of the dish by capillarity and then ran by gravity down the hanging end and dripped into the beaker where the quantity was measured.

c. In selecting textiles which were typical of bibulous and non-bibulous insulation, the diameter of the individual fibers was chosen as the principal criterion. It was thought that two intersecting fine fibers might be drawn together by the surface tension of the water on them and that water would be wicked along the line of contact. If their diameter were greater, their rigidity would be greater; and surface tension could not draw them together to form a wicking path.

d. The types of cloth tested consisted of a napped cotton flannel, 3.4 oz. per square yard, an olive drab (OD) wool serge weighing 15 oz. per square yard, and a Harris tweed weighing 12 oz. per square yard. The cotton was selected as a typical fine fibered material with good wetting characteristics. The OD serge was chosen as representative of a closely woven woolen material with relatively fine fibers, while the Harris tweed was chosen for its coarse and harsh fibers. All materials were wetted by dipping and wringing out slightly so that they contained from 150 to 200 per cent water.

4. Results and Discussion

a. Wicking Experiments

(1) The experiments on wicking showed differences in the materials tested. When the cotton strip was used, it started dripping from the lower end within five minutes and filled the 100 ml. beaker in about half an hour. The OD serge did not start dripping for two hours and filled the beaker in 12 to 14 hours. The Harris tweed did not start dripping for several days, and it was impossible to fill the beaker under it with water. When the cotton was wicking it appeared wet, the nap being held down to the body of the cloth by surface tension. The OD serge, however, appeared on casual inspection to be dry except for the corner from which it was dripping. Closer inspection disclosed that the center of the material was wet even though the nap appeared dry. The Harris tweed

definitely would not wick if the level of the water in the upper evaporating dish was lower than one-half inch from the rim. When wicking did occur, the cloth did not appear wet and hardly even damp. Although such results are qualitative only, they do indicate the wicking properties of the three materials are quite different.

b. Single Layer Materials

(1) Figure 6 shows typical power ratios for drying cotton flannel, OD wool serge, and Harris tweed. The curve for cotton shows a high initial power ratio which continues fairly constant and then drops suddenly to unity, suggestive of the bibulous material. This particular sample had an original moisture content of 46 grams of which all but 8 grams had evaporated after 40 minutes. While the power ratio of about 1.8 is not that predicted by theory for a completely bibulous material (2.52), it should be remembered that quantitative agreement is not expected. The average apparent latent heat for this material from several experiments was 633 calories per gram compared with the computed result of $1.687 \times 595.4 = 1004$ cal. per gm. for completely bibulous material.

(2) The curve for OD serge shows a much lower initial power ratio than cotton. It continues to decrease slightly for about 80 minutes and then falls to unity in a manner analogous to that predicted for a non-wicking material. It is probable that the moisture in this sample of material was originally mainly concentrated in the center woven part inasmuch as the nap appeared dry. The initial portion of the curve would then represent drying of this portion. It was noticed shortly after drying commenced that the nap on the cold side became interspersed with fine droplets of moisture resembling a heavy deposit of dew. Since this represented moisture driven to the cold side and condensed, and since there was no evidence of it before drying, it is concluded that most of the moisture was originally in the center of the textile. The decreasing portion of the curve, then, represents drying of this moisture in the cooler nap. The average apparent latent heat for this material was 426 calories per gram. This would indicate that although there was some wicking, the amount was much less than in cotton.

(3) The curve for Harris tweed shows a somewhat similar shape to that of the OD serge. The initial part of the curve extends to about 150 minutes and is much lower in power ratio. The mean value of several experiments gives an apparent latent heat of 278 calories per gram. The computed value for completely non-bibulous material is 271 calories per gram. This indicates that little, if any, wicking takes place. The same accumulation of moisture in the nap of the fabric was noticed as with the OD serge.

c. Double Layer Materials

(1) Figure 7 shows three typical curves obtained with two layers of cotton fabric. That in which both layers were wetted shows two portions where the power ratio remains relatively constant. The first one represents the drying of the warmer layer with wicking within it. The drop between 20 and 40 minutes represents the drying of this layer and forcing of its moisture into the cooler layer. Thus, it can be concluded that there was wicking within layers but not between layers. The temperature recorded between the two layers of material was initially 74°F., dropped to 66°F. at 40 minutes, and to 63°F. at 50 minutes. At 140 minutes, it had risen to 68°F. This fits qualitatively with the theory mentioned above that in non-bibulous insulation the temperature should be initially above the mean, drop below it, and finally return to it (see 2 c (3), above). The drop in temperature also coincides with the drop in power ratio indicating drying of the warmer layer. The apparent latent heat was 670 calories per gram.

(2) The curve for two cotton layers in which the lower or warmer layer only was wet shows similar characteristics. The initial power ratio is, however, very much higher. The initially dry cooler layer is a good insulator conducting only sensible heat and, therefore, the temperature between the two layers rose as high as 86.1°F., while there was rapid extraction of heat from the warmer layer. The first drop in power ratio represents the completion of movement of moisture from the warmer to cooler layer. This is accompanied by a decrease in temperature of the mid-layer to 65°F., and a decrease in moisture evaporated from 1.35 grams per minute to 0.6 grams per minute corresponding to the drop in power ratio from 3.1 to 1.5. The curve after 60 minutes represents drying of the cooler layer.

(3) The last curve, Figure 7, represents the power ratio when only the cooler layer was wetted. The initial moisture content was 137 grams or 450 per cent of the dry weight of the outer layer of cloth. The initial irregular part of the curve represents wicking or, perhaps, physical dropping of moisture into the warmer layer and subsequent evaporation from it. After 130 minutes there was only 45 grams of moisture in the insulation and, presumably, water movement between layers practically ceased. The temperature between the layers was initially 61°F., and rose to 70.6°F. when the power ratio fell.

(4) The experimental results can be partially interpreted by the theory proposed. Both theory and experiment agree qualitatively with regard to apparent latent heat, variation in temperature between two wetted layers and time required for total drying. The power ratio curves for the OD serge and Harris tweed are not similar to those predicted by the theory for an initially uniformly wetted non-bibulous material. Experiment shows an almost constant power ratio in the initial drying stages while the

theory predicts a power ratio initially as high as for bibulous, but which drops rapidly with time. The nap on both these materials initially appeared dry. Perhaps, the material did not wet uniformly on immersion and light wringing, and most of the water was concentrated on the closer woven central portion of the fabric and less was in the nap.

5. Application to Clothing

a. It is perhaps obvious that if a man's clothing is wetted in cold weather, he will lose heat and rapidly become cold. Such an occurrence may be due to falling into water or being out in a heavy rain so that he gets "soaked to the skin" both literally and figuratively. Should such a man have to continue wearing the wet clothing until dry, it is clear from the above results that he would lose less heat in the type of clothing of which tweeds and woolens are typical than if he were in the cotton type. Moreover, if the man were in a position where he could soon change his wet clothing, he would still become less chilled if it were of the non-bibulous type since the initial power ratio is less.

b. This analysis also explains why a wool bathing suit is warmer than a cotton one after getting out of the water.

c. In extreme cold, the outer layers of the clothing are below freezing and the water vapor condenses to form frost crystals. Such crystals are, of course, completely non-bibulous below freezing. If the non-bibulous theory is strictly applicable, frost which remains in the outer layers of Arctic clothing should not contribute greatly to heat loss.

d. A third application is to men who are exposed to a light drizzle of rain or fog. Such a light rain has little momentum when it strikes the clothing and so lands on the outer layers. If the clothing is of the non-bibulous type, there are only slight capillary forces tending to draw moisture to the inner layers. Opposing this is the tendency of the heat to drive the moisture out. Thus, it will tend to remain in the outer layers only and the cooling, due to evaporation, will be small. With bibulous material, such drizzle or fog is soaked right into the skin and chilling results. It is probably for this reason that rough tweeds are popular in such typical wet-cold areas as Scotland.

e. It is hoped to follow this paper by a study of heat transfer through insulation when moisture is being produced at the warm surface, a situation analogous to that of the clothed sweating man. Meanwhile, a few preliminary remarks might be made on a new interpretation of the so-called "Brynje", or net, underwear. When the skin of a man is wet, it has been shown that condensation will occur on all parts of his clothing

(see 2 b (1), above). Hence, under the conditions of the calculations, for completely wet insulation (Figure 3), he can lose 2.52 times the heat that he would if he were not sweating and his clothing were dry. When he stops sweating in non-bibulous clothing, it is initially wet but as time progresses the inner layers dry and the rate of heat loss decreases. How rapid this decrease will be is dependent on the amount of moisture accumulated. If, however, a Brynje vest is considered as an inner layer of holes or as air spaces, then moisture cannot accumulate in this space. In effect, the insulation is such that the inner layer can accumulate no moisture. If the inner quarter of the insulation consists of an air space, then the change from sweating to non-sweating corresponds by Figure 3 to an immediate change in power ratio from 2.5 to 1.5 when the clothing is wet. With no air space or Brynje, there is no such immediate change in power ratio. Such an interpretation of the action of Brynje vests probably supplements rather than supercedes previous ones.

6. Conclusions

a. A theory of heat transfer through wet materials has been developed which is based on evaporative cooling. It predicts that:

(1) When bibulous materials (i.e., wicking materials) are drying, the additional heat transferred due to the presence of moisture is about one and one-half times the latent heat of the water evaporated.

(2) When non-bibulous materials are drying, the additional heat transferred is only about one-half of the latent heat of the water evaporated.

(3) The total drying time of bibulous materials is shorter than that of non-bibulous materials.

(4) The rate of heat loss through wet insulation is a function of the location of the moisture. If the part of the insulation nearer the heat source is dry, the rate is much less than if it is wet.

b. Harris tweed suiting, OD serge, and cotton flannel were shown to have very different wicking characteristics and to behave qualitatively in accordance with the theory.

c. Non-bibulous fabrics are advantageous for body heat conservation in cold weather whenever wetting may be a problem.

7. Acknowledgment

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TEMPERATURE GRADIENTS THROUGH UNIT THICKNESS OF INSULATION

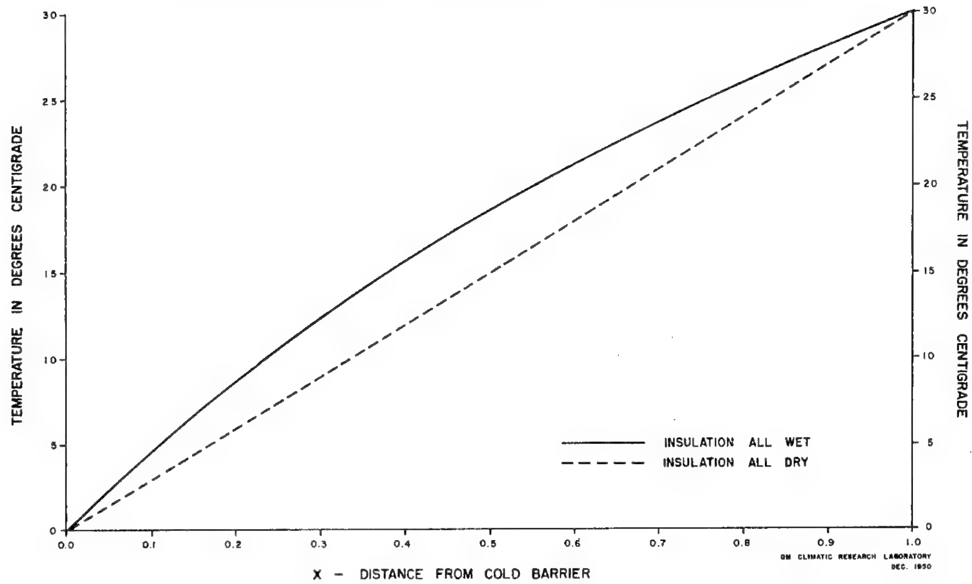


FIGURE 1

TEMPERATURE GRADIENTS THROUGH UNIT THICKNESS OF NON-BIBULOUS INSULATION

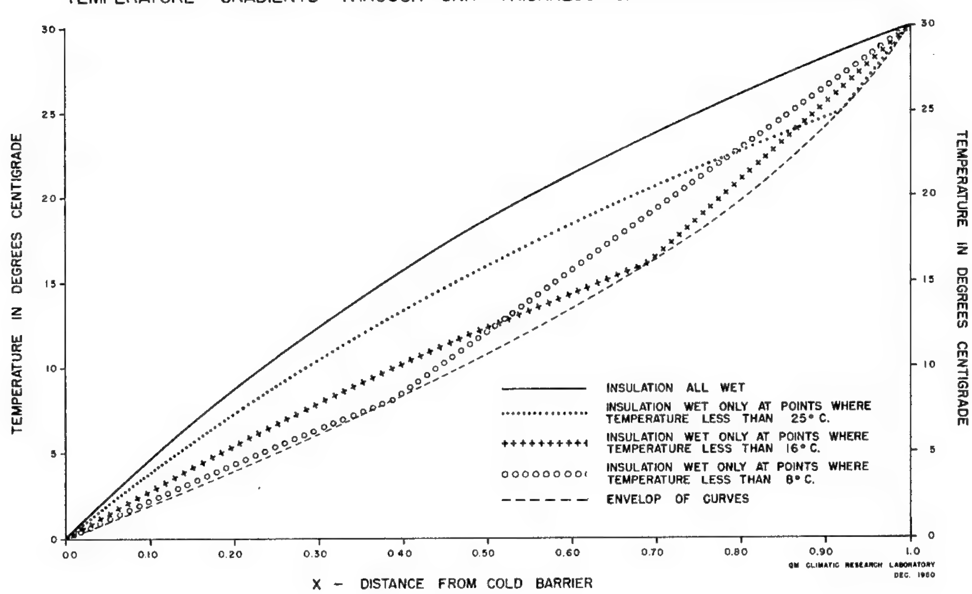


FIGURE 2

POWER RATIO OF NON-BIBULOUS INSULATION PLOTTED AS FUNCTION OF PENETRATION OF MOISTURE

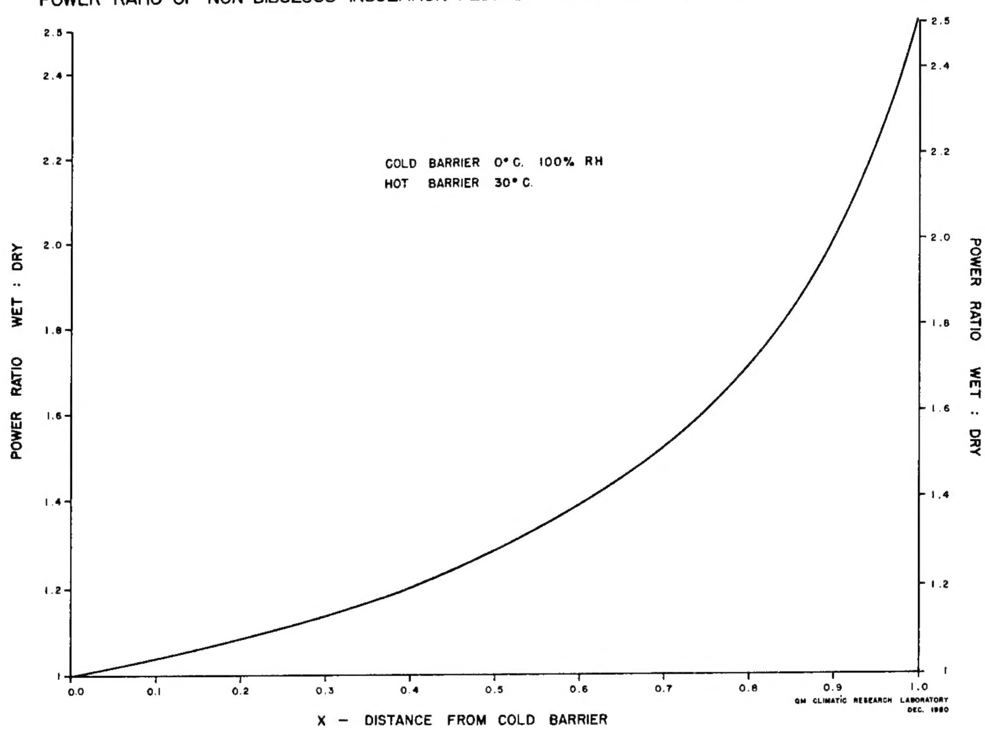


FIGURE 3

RELATIVE MOISTURE CONTENT AND POWER RATIO OF BIBULOUS AND NON-BIBULOUS WET INSULATION PLOTTED AS FUNCTIONS OF DRYING TIME

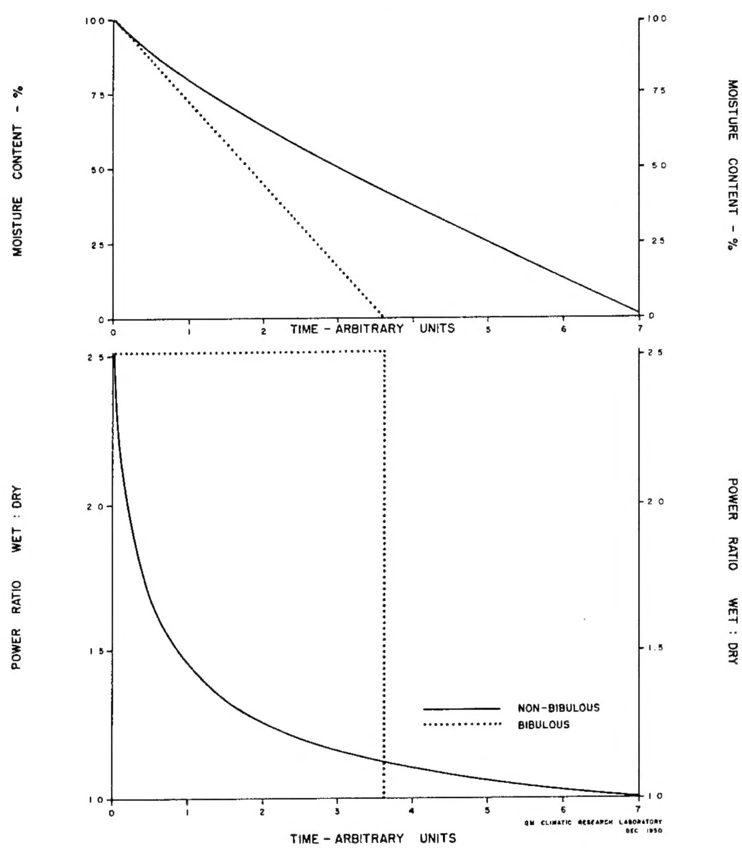


FIGURE 4

TYPICAL CALCULATED MOISTURE DISTRIBUTION IN NON-BIBULOUS INSULATION WHILE DRYING
(From Initially Uniform Moisture Distribution)

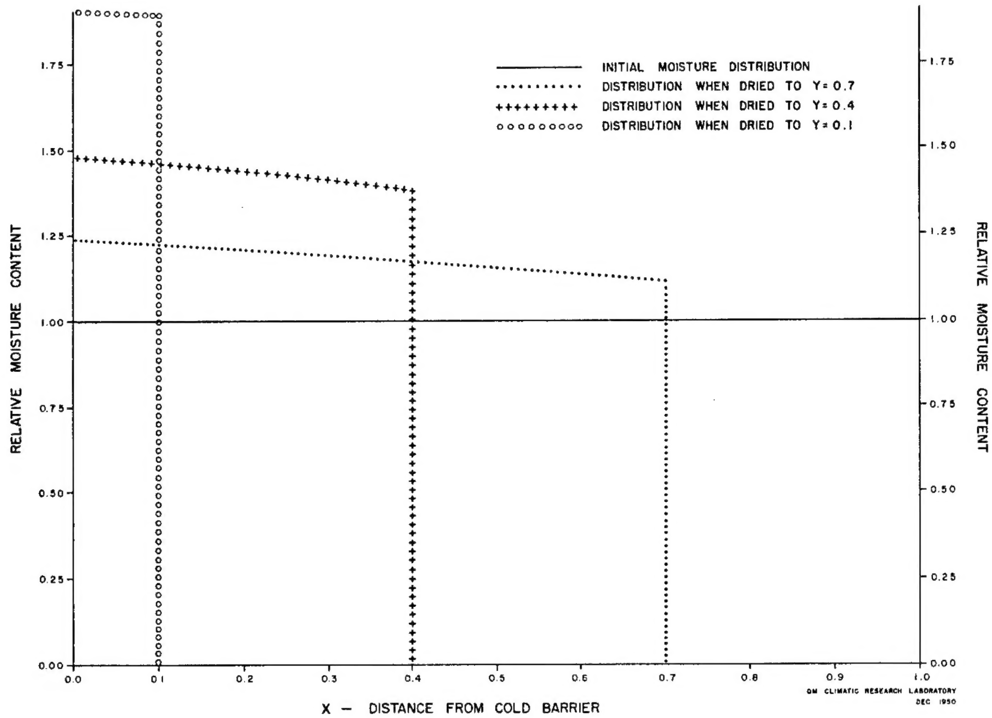


FIGURE 5

EXPERIMENTAL CURVES OF POWER RATIO MEASURED ON GUARD RING FLAT PLATE COVERED BY WETTED TEXTILE MATERIALS

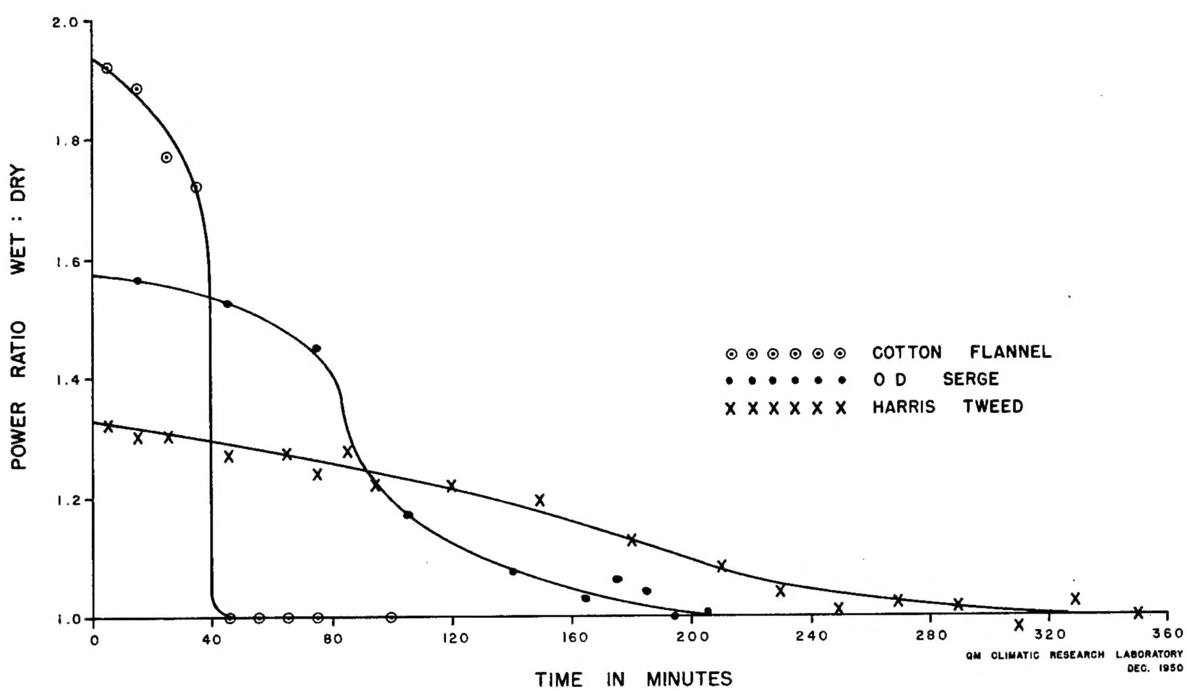
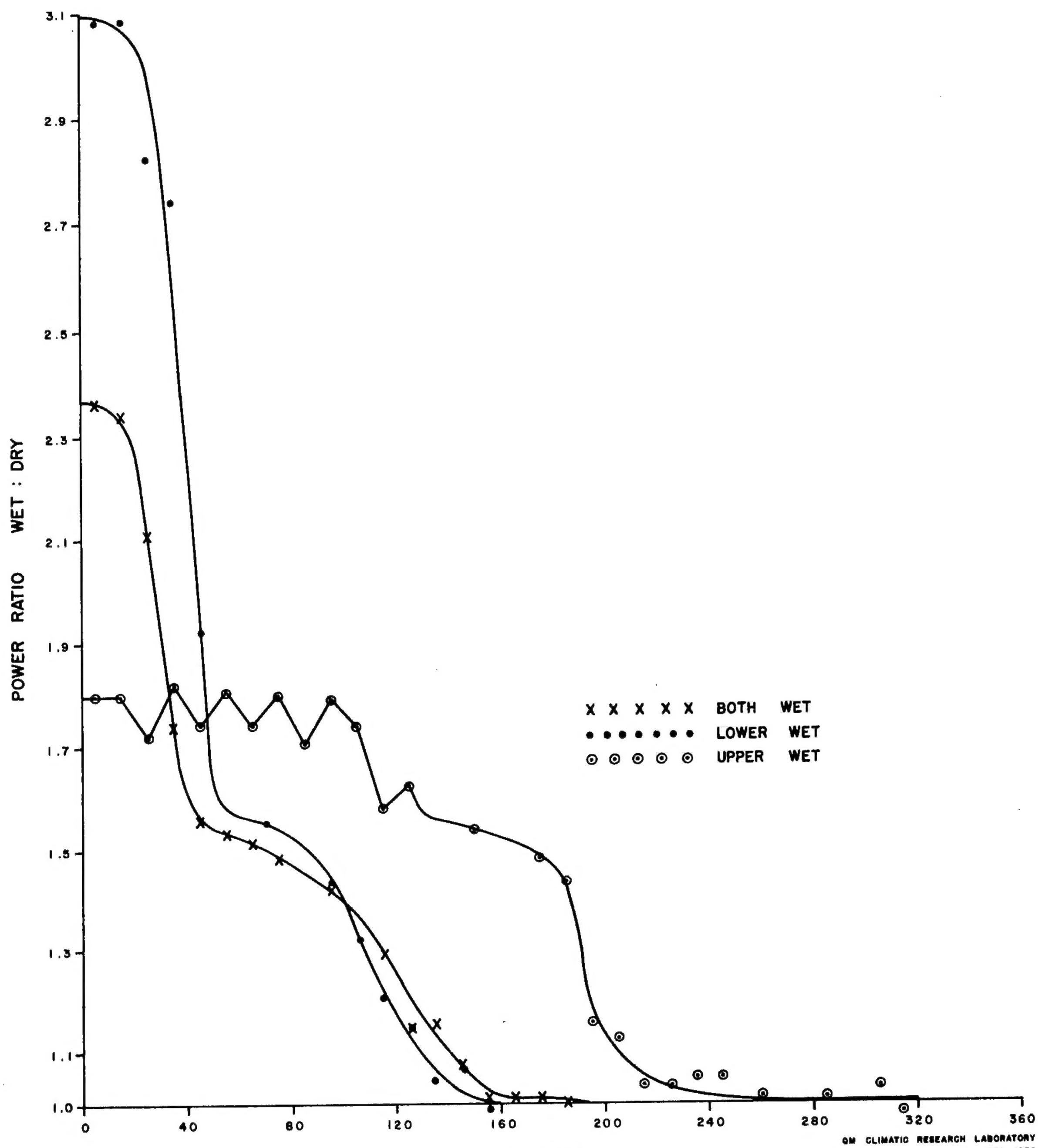


FIGURE 6

EXPERIMENTAL CURVES OF POWER RATIO MEASURED ON GUARD RING FLAT PLATE COVERED BY WETTED TEXTILE MATERIALS

(Two Cotton Layers)



TIME IN MINUTES

FIGURE 7

D I S T R I B U T I O N   L I S T "C"

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